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REOCCUPATION OF THE DEVILS MOUNTAIN GPS STRAIN NETWORK, NORTHWESTERN WASHINGTON

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TECHNICAL ABSTRACT

Velocities from a dense GPS network in the northern Puget Lowland and San Juan Island region of northwestern Washington supports geological and geophysical interpretations and suggests active deformation on several throughgoing fault systems. The Northwest Washington Geodetic Network (NWGN) consists of 27 sites along an east-northeast transect stretching from the Pacific coast on the Olympic Peninsula to east of the northern Cascade Range. GPS sites within the network are concentrated along a broad north-south swath covering the San Juan Islands, northern Puget lowland, western Cascade foothills, and the eastern Olympic Peninsula. The network provides the site density needed to assess whether or not specific fault zones underlying the region are active. Twenty four sites of the NWGN were successfully reoccupied in 2001, five years after the initial network deployment in 1996. Site occupations in 1996 ranged from 24 to 48 hours and in 2001 all sites were occupied for 48 hours. The NWGN velocities are consistent with those determined for the wide aperture Pacific Northwest Geodetic Array but due to increased network density provide greater insight into the spatial variability of the regional velocity field. When effects of the locked Cascadia megathrust are removed, a residual velocity field yields differential motions of up to 5 mm/yr within the NWGN. The velocity field is heterogeneous with significant variations in azimuth and magnitude occurring in the vicinity of major fault systems. Significant differential velocities are observed across the northern Hoods Canal fault system, the South Whidbey Island fault, and the Devils Mountain fault of the Puget Lowland and San Juan Islands. A previously unrecognized fault, located along the eastern margin of the San Juan Island Group and referred to here the Lummi Island fault, may be active based on the distribution of GPS site velocities. Based on our preliminary analysis, velocity gradients are greatest near major fault systems and are consistent with distortion of a far field displacement field by locked segments of active faults. Based on these observations, the seismic threat posed to northwestern Washington and southwestern British Columbia by throughgoing fault systems may overshadow the hazard presented by continued ENE-WSW shortening across the Cascadia megathrust.

NON-TECHNICAL SUMMARY

The Global Positioning System (GPS) was used to determine the rate of motion of several sites in northwestern Washington along a transect stretching from the Pacific coast (Olympic Peninsula), through the northern Puget lowland and San Juan Island region, and across the northern Cascade Range. The GPS

sites are part of a regional network, the Northwestern Washington Geodetic Network (WNGN) deployed by the University of Idaho. During this research project, the positions of monuments located in bedrock or secured on rods driven to refusal in poorly consolidated sediments were measured. The sites were originally measured in 1996 and were reoccupied in 2001. Each site was occupied using dual frequency GPS receiver-antenna systems mounted on tripods (Leica GPS equipment) for 24-36 hours in 1996 and for 48 hours in 2001. The positioning data were processed together with data from continuously monitored GPS sites of the Pacific Northwest Geodetic Array, which allowed location of the NWGN in a reference frame fixed on stable North America. Coordinate positions for NWGN sites have precisions of ~3-4 mm (horizontal). Changes in the position of the GPS sites over the 5 year interval between measurements yield displacement rates, or velocities, of the GPS sites in mm/yr. GPS site velocities decrease from the ~18 mm/yr toward the northeast along the Pacific coast to essentially no displacement in the region east of the northern Cascade Range. Part of the displacement is related to the locked Cascadia subduction zone. When the effects of the locked subduction zone are compensated, a residual velocity exists and is related to north-south shortening within the Puget lowland and San Juan Island region of northwestern Washington. The spatial organization of the residual velocity field is not smooth and substantial changes in velocity direction and magnitude occur for GPS sites located near active faults. In light of the fact that our results are based only on two occupations, we cannot preclude the possibility that additional measurements will smooth the spatial heterogeneity in the velocity field. Nevertheless, the spatial correspondence between active faults and the departures from a smooth regional velocity gradient cannot be discounted out of hand. The changes in velocity magnitudes and directions are consistent with active strain accumulation on several faults and a resultant distortion of the regional velocity field.

TECHNICAL REPORT

REGIONAL SETTING

Subduction along the northern Cascadia margin (Fig. 1) is estimated at 34 mm/yr along a N50E axis (DeMets and Dixon, 1999), and geodynamic models of surface motions (Dragert et al., 1994; Fluck et al., 1997) support the interpretation that the subduction zone is locked and actively accumulating strain. Within the North American plate, most earthquakes are less than 35 km deep (e.g., Ludwin et al., 1991; Rogers and Horner, 1991), and have a distribution that changes along strike in the forearc basin. South of the Strait of Juan de Fuca, earthquakes are concentrated in the Puget Lowland and Cascade foothills, whereas to the north, the zone of seismicity broadens in a region from central Vancouver Island to the western Cascade foothills. Seismicity is greater in the south and together with the distribution of historic earthquakes of magnitude 3 and greater (Fig. 2) suggests that the southern region is more tectonically active.

First-motion solutions are rare due to the small number of recorded large to intermediate magnitude earthquakes (M>3) since inception of the regional seismic network less than three decades ago. Nevertheless, earthquake focal mechanisms in the southern Puget Lowland are dominated by strike-slip first-motions consistent with right-lateral motion on N-S trending faults and a few earthquakes yielding thrust mechanisms consistent with reverse oblique slip on WNW-ESE trending faults (Ludwin et al., 1991). In the northern part of the Puget Lowland, only the 1985 earthquake near the Stillaguamish River drainage yields reliable results and is consistent with right-oblique motion on a WNW-ESE fault.

The Puget Lowland is underlain by young (~40 Ma to recent) sedimentary and volcanic rocks cut by the Coast Range boundary fault system. The faults are active, at least locally, and consist of curvilinear N-S faults bordering the Cascades (foothills) and Olympic Mountains (Hoods Canal) and WNW-ESE to NW-SE trending faults underlying and controlling much of the morphology of the intervening lowland (Fig. 3). The N-S faults are interpreted to be strike-slip systems that bound the Puget Lowland and the WNW-ESE to NW-SE faults typically have right-oblique reverse slip.

The age of last motion on specific faults is poorly constrained. In several cases displacements clearly are no older than Eocene in age but their last episodes of motion are obscured by the dense vegetation and lack of preserved surface features. Nevertheless, a few faults may be as young as late Quaternary and conceivably are still active (Gower et al., 1985; Bucknam et al., 1992; Johnson et al., 1994, 1995, 2001). Earthquake epicenters are broadly distributed throughout the region, further strengthening the idea of active movement on faults, but correlation between seismicity and recognized fault systems has been lacking (Ludwin et al., 1991).

The Pacific Northwest Geodetic Array (PANGA) provided the first regional velocity framework which varies from ~18 mm/yr of NE displacement along the Washington coast to only a few mm/yr east of the Puget Lowland (Khazaradze et al., 1999; Miller et al., 2001). Three-dimensional elastic modeling (Miller et al., 2001) suggests that the velocity field is a manifestation of recoverable strain related to ENE convergence between the Juan de Fuca plate and North America (Fluck et al., 1997) and long-term deformation related to the northerly migration of the Cascadia forearc. In southwestern British Columbia, plate convergence is essentially head-on and the forearc does not migrate northward, and thus behaves as a tectonic buttress. From south to north, residual velocities range from greater than 7 to less than 2 mm/yr and produce a substantial N-S strain gradient in the Puget lowland region.

At question is how the regional strain is accommodated by fault systems underlying the Puget Lowland and San Juan Island region of northwestern Washington. To address this question, the Northwestern Washington Geodetic Network (NWGN) was first deployed across several major fault systems in the northern Puget Lowland and San Juan Island region in 1996. The network was reoccupied in 2001 and based on the two occupations provides a regional velocity field suggesting that strain accumulation is widespread and that several major fault systems are active.

NETWORK CONFIGURATION AND OCCUPATION

The NWGN uses existing benchmarks in bedrock where possible and benchmarks fixed to rods driven to refusal, particularly in areas of the Puget Lowland south of the Devils Mountain fault. The network was designed to record regional ENE shortening and more significantly N-S displacement across several known or suspected active faults in northwestern Washington. During the first deployment in August 1996, twenty seven (27) sites were occupied continuously for between 24 and 36 hours in simultaneous deployment of six Leica dual frequency receivers. During each deployment, five new sites were occupied with one site of the previous deployment retained to link elements of the network. Twenty one (21) network sites form a north-south swath across the San Juan Islands extending south into the northern part of the Puget lowland to the latitude of southern Whidbey Island and northern Hoods Canal (Fig. 5). The remaining sites lie along the transect stretching west to the Pacific coast (Forks) and east of the northern Cascades (Starvation Mountain). The network was reoccupied in August, 2001 using six Leica dual frequency receivers and choke-ring antennas. Occupation of each site was continuous for 48 hours. Of the twenty-seven original sites, twenty-four were successfully reoccupied. Two sites were destroyed, one by road paving and the other by bank erosion, and one site produced irresolvable multipathing problems.

DATA PROCESSING AND UNCERTAINTY ANALYSIS

The data were processed using BERNESE (4.2) together with data from International GPS Service (IGS), Western Canada Deformation Array (WCDA), and PANGA reference sites to align the network solution with the ITRF00 reference frame. BERNESE utilizes baseline double-difference processing, in which common error sources such as satellite ephemeredes, atmospheric delays, and clock errors are eliminated. Cycle slip detection and repair was concluded for each session and carrier phase ambiguity was resolved. Ocean loading parameters were calculated and included in coordinate solutions.

For 1996 three reference sites were sufficiently close not to adversely impact coordinate solutions by large baseline lengths (ALBH, DRAO, QUIN) and in 2001 eight sites were available for fiducial control (ALBH, DRAO, QUIN, SEAT, SATS, LIND, SEDR, NEAH). Site coordinate solutions were processed in 8 hour arcs and combined to produce position solutions for each site. Coordinate solutions from all sessions are combined to produce a total velocity field shown in Figure 6 in a frame fixed on DRAO, located in south-central British Columbia (Fig. 5).

Velocities are shown with 95% confidence ellipses determined by a propagation of coordinate uncertainty. Formal errors are scaled root mean square values for coordinate uncertainty from each session solution summed for all sessions and divided by n-1/2. To account for the five year time span between observations, we include a gain factor g calculated using the formulation of Brockmann (1996):

$$g = (3k2 - 3k + 1)1/2$$

where k is the total time span in years. Random walk uncertainty of 1.3 mm(yr)-1/2 was added to accommodate benchmark instability for sites located in unconsolidated or poorly consolidated sediments (Langbein and Johnson,1997).

Although the coordinate statistics are good, the quality of the velocity field may be misleading because it is based only on two occupations. The stability of site velocities cannot be tested directly by coordinate time-series. The possibility of site blunders cannot be discounted.

GPS VELOCITY FIELD

The NWGN velocities are shown together with published PANGA velocities (Fig. 6) transformed into a fixed DRAO frame (Fig. 5). Although DRAO has an unresolved north-northeast motion of less than 2 mm/yr with respect to a stable North America (Miller et al., 2001), this motion does not pose a significant problem for this analysis.

Where NWGN and PANGA sites are close, velocities for the continuous and campaign solutions are essentially the same (Fig. 6). From west to east, the NWGN and PANGA regional velocity field decreases from NE-directed velocities of ~18 mm/yr along the Pacific coast to no statistically significant motion east of the Cascades. Velocities decrease rapidly from the Pacific coast toward the Puget lowland and San Juan Islands. Relatively high velocities along the Pacific coast is attributable to elastic strain accumulation associated with the locked Cascadia megathrust, which based on elastic dislocation models produces a detectable but diminishing contribution as far east as the Cascade foothills (Miller et al., 2001).

Overall, the regional velocity field shows significant heterogeneity with site velocities deviating from the regional pattern with proximity to major fault systems (Fig. 7). Specifically, in the vicinity of WNW-ESE and NW-SE trending structures like the Devils Mountain and South Whidbey Island fault zones and NNW-SSE and N-S structures like the Lummi Island and northern Hoods Canal faults, velocities show an anticlockwise rotation and/or are reduced in magnitude.

We consider it unlikely that the spatial correspondence between major fault zones and deviations of site velocities from the regional trend is fortuitous, particularly in light of the similarity between PANGA and NWGN velocities where sites are close. Rather, we conclude that the velocity field in the northern Puget Lowland does not conform to a smooth northeasterly decreasing gradient. Although still speculative, we assert that the Hoods Canal, South Whidbey Island, Devils Mountain, and Lummi Island faults are active and imparting a signal recorded in the regional velocity field.

CONCLUSIONS

1. A regional velocity field based on two occupations of 24 sites of the Northwestern Washington Geodetic Network (NWGN) is broadly consistent with the regional velocity gradient (showing a northeasterly velocity decrease from the Pacific coast to the Cascade Range) recorded by wide aperture results from the Pacific Northwest Geodetic Array (PANGA).
2. The greater spatial resolution afforded by the NWGN illustrates that the regional velocity gradient is not smooth and that velocities of sites in proximity to major fault systems underlying the northern Puget Lowland and San Juan Island region of northwestern Washington are rotated anticlockwise and/or reduced in magnitude.
3. Local distortion of the regional velocity gradient is consistent with active deformation along several north-northwest and west-northwest trending faults of the northern Cascadia forearc basin regional velocity field

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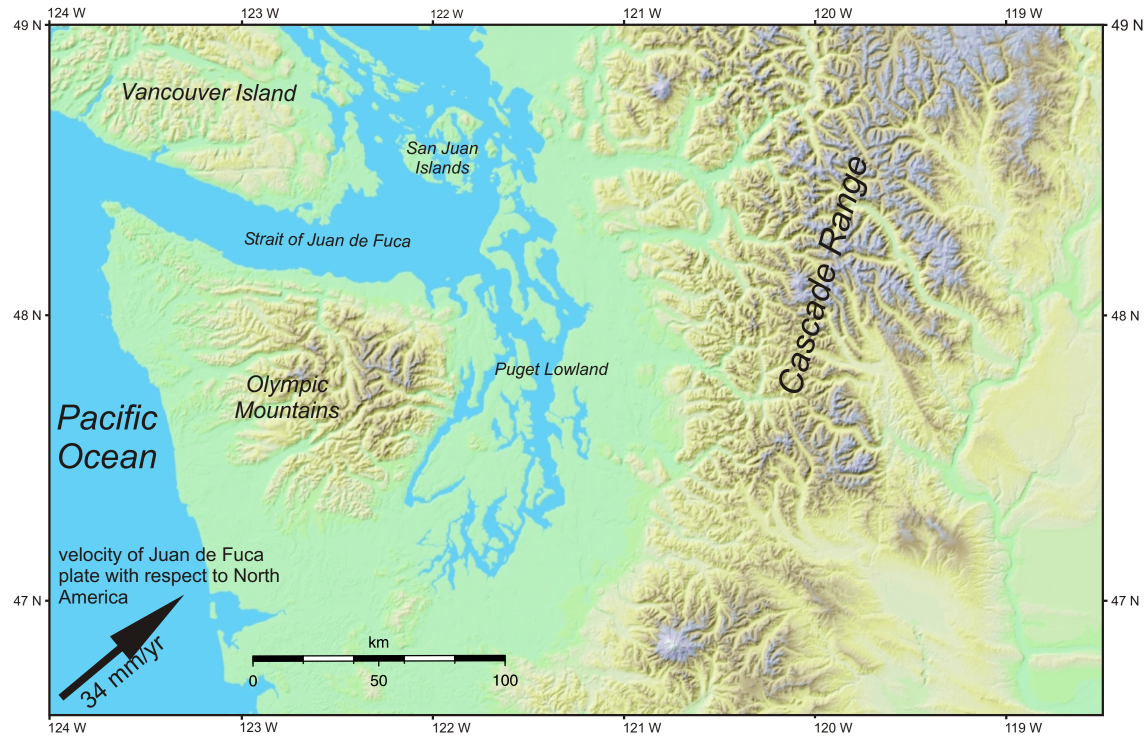

Figure 1. Northern Cascadia margin of western Washington and southeastern British Columbia. Convergene between the Juan de Fuca and North American plates is 34 mm/yr along an axis of N50E.

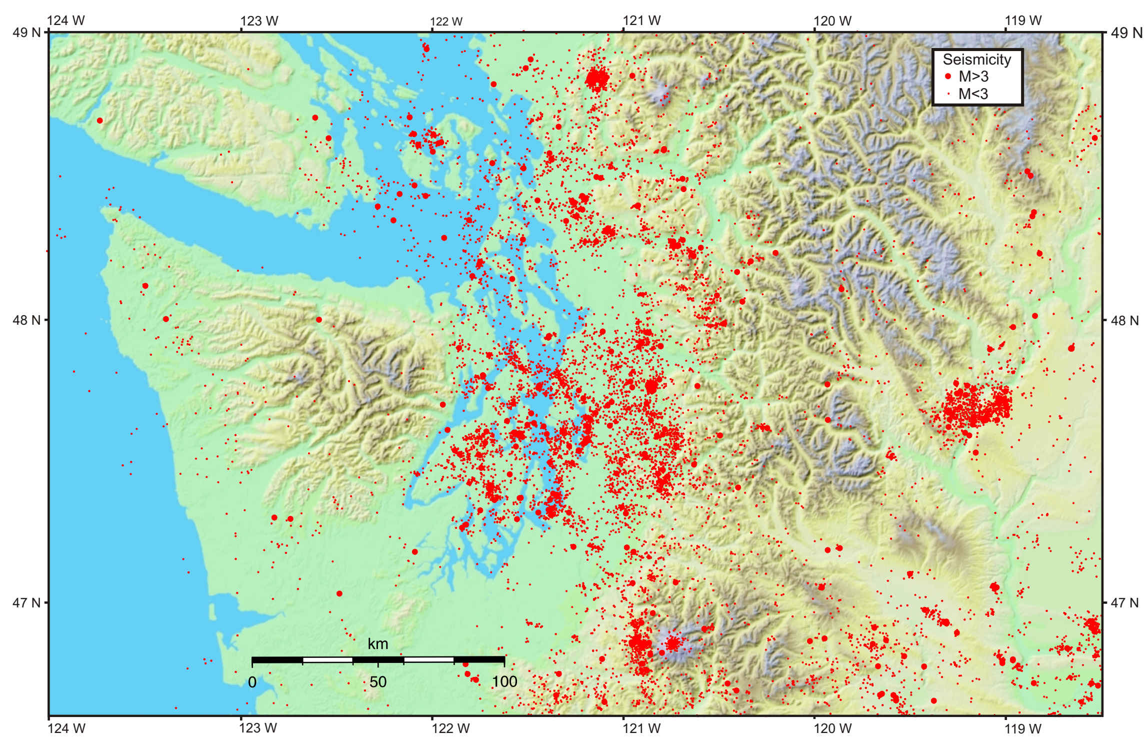

Figure 2. Earthquake epicenters in northern Cascadia over the period 1963 to 2002 (source: Advanced National Seismic System)

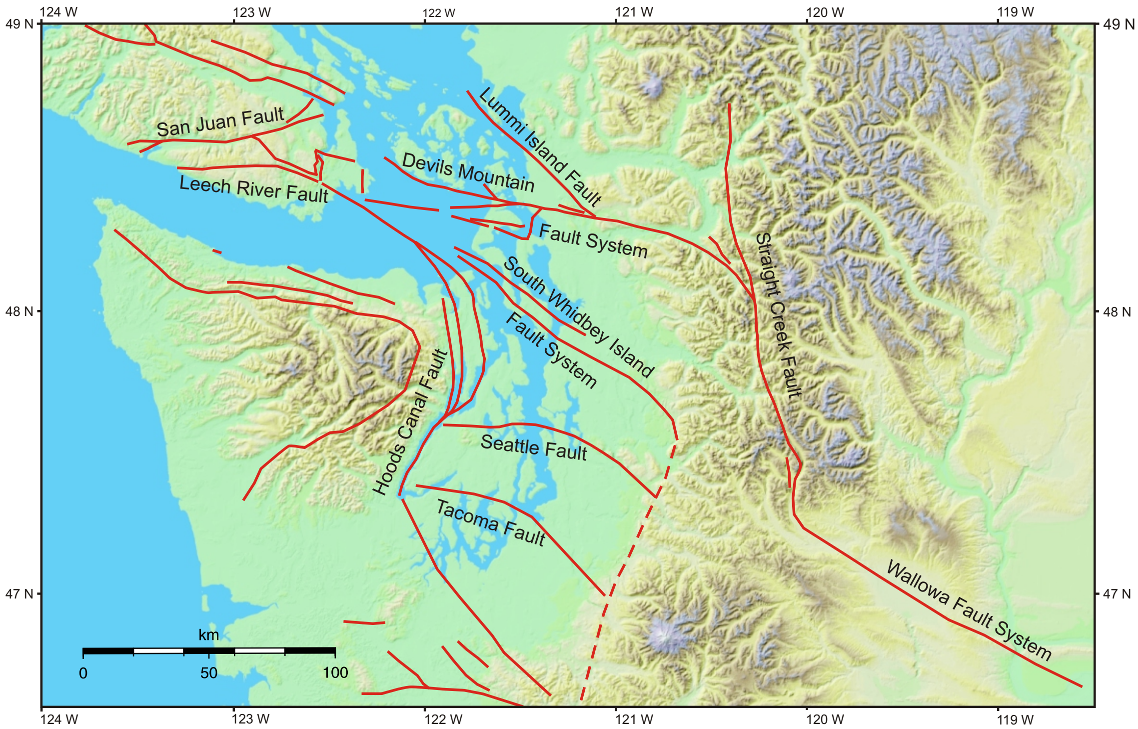

Figure 3. Major fault systems underlying the forearc basin of northern Cascadia.

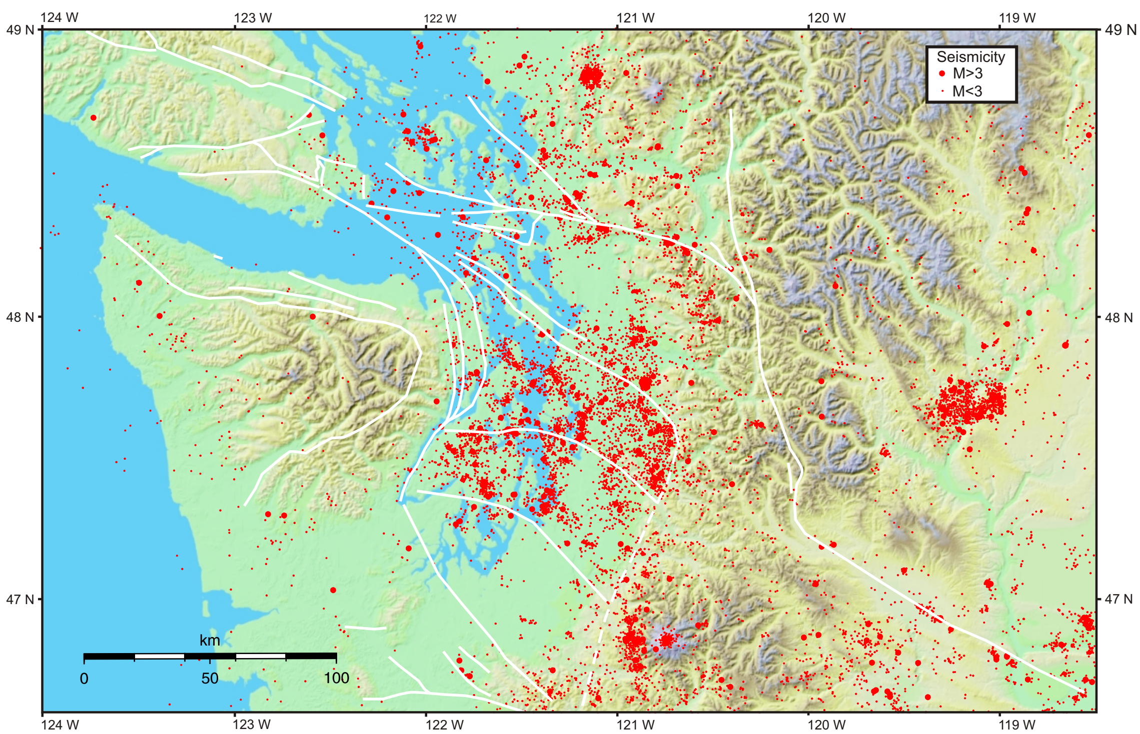

Figure 4. Seismicity and faults of northern Cascadia. Concentrations of epicenters suggest spatial correspondence with faults in some cases but no clear relation to known or suspected faults in others.

Figure 5. Northwestern Washington Geodetic Network (NWGN) and reference sites. Reference sites are operated as parts of the Pacific Northwest Geodetic Array (PANGA), the Western Canada Deformation Array (WCDA), and the International GPS Service (IGS). For the 1996 NWGN occupation, only sites ALBH, DRAO, and QUIN with relatively short baselines were available for fiducial control. For the 2001 occupation of the NWGN, eight reference sites (ALBH, DRAO, NEAH, SATS, SEAT, SEDR, LIND, and QUIN) were employed.

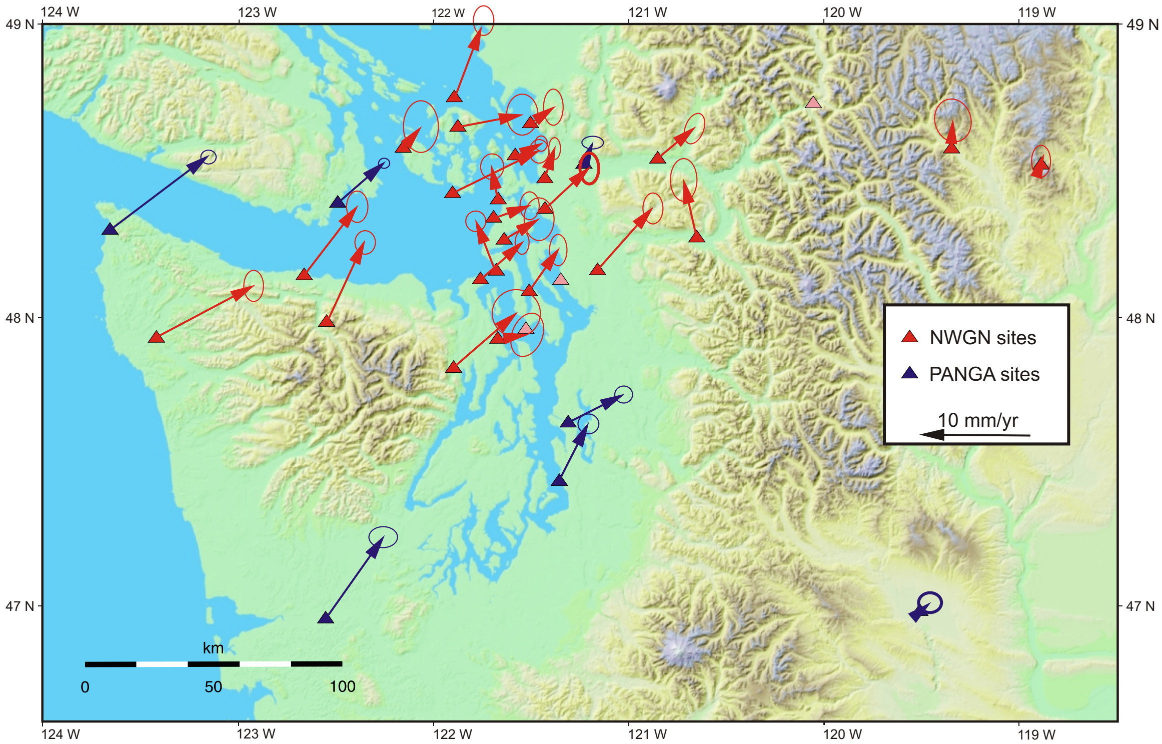

Figure 6. Regional velocity in a fixed DRAO reference frame (Fig. 5). Note the similarity in NWGN and PANGA velocities where sites are in proximity. The greater spatial density of NWGN sites suggests significant spatial variability in site velocities across the network. A progressive decrease in regional velocity northeast from the Pacific coast to the Cascade foothills is attributable in to elastic strain associated with the locked Cascadia megathrust and permanent north-south shortening in the Cascadia forearc basin (Miller et al., 2001). Velocity field heterogeneity observed in the northern Puget Lowland and San Juan Island region of the NWGN is statistically significant; within limits of a velocity field determined by two network occupations.

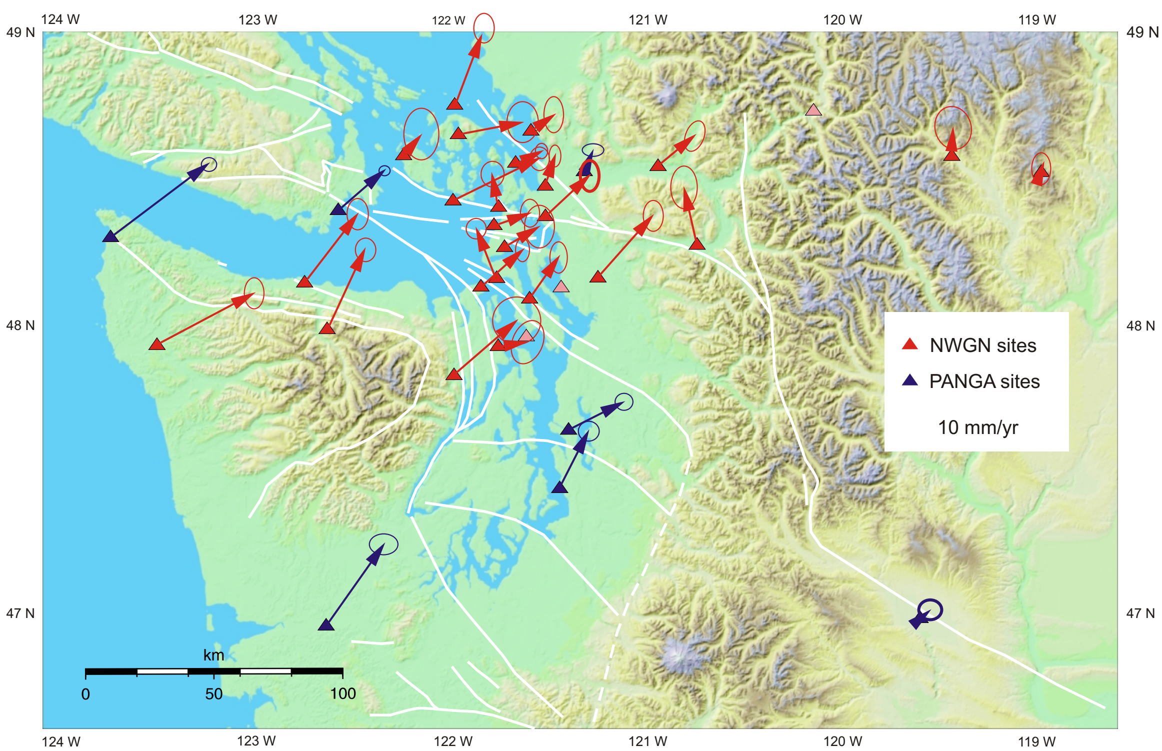

Figure 7. NWGN and PANGA velocity field shown together with traces of major fault systems in the forearc basin of northern Cascadia. In proximity to major fault systems, NWGN site velocities show anticlockwise and/or magnitude reduction with respect to a systematic decrease in the regional velocity field from the Pacific coast to the Cascade Range.